The aerosol optical depth by components from the Multiangle Imaging SpectroRadiometer (MISR)

: applications to evaluating chemistry transport models and studying optical properties of wildfire-induced aerosols

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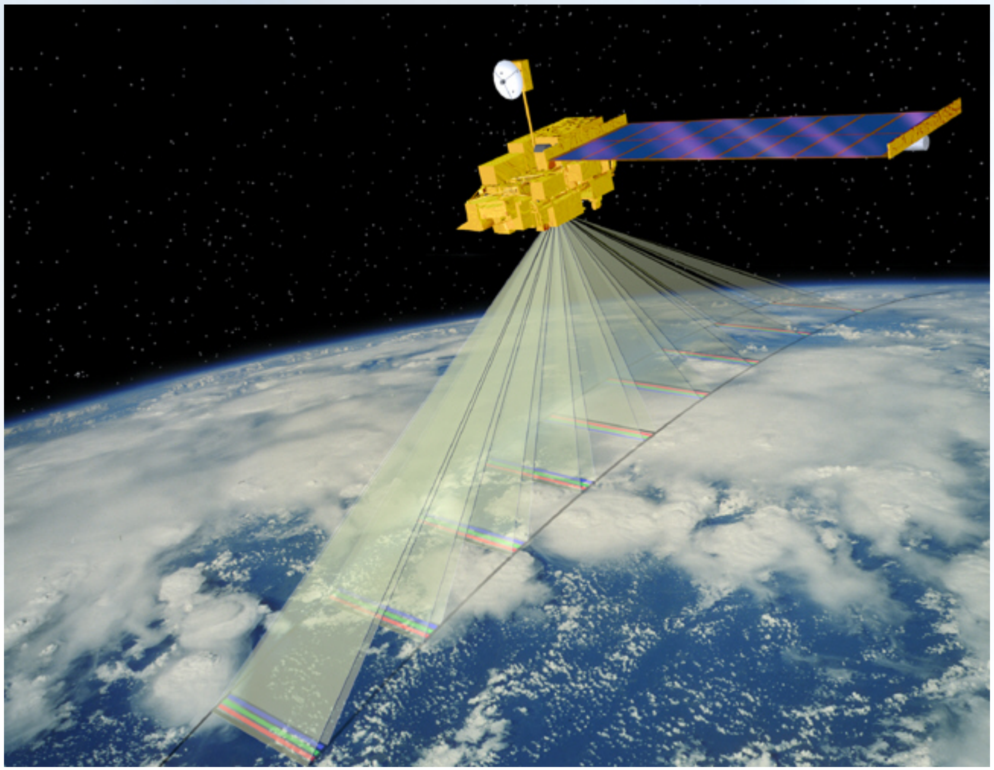
Outline

- Introduction
  - Multi-angle Imaging SpectroRadiometer (MISR)
  - MISR Joint Aerosol (JOINT_AS) Product
- Comparison of MISR Joint Aerosol Product with simulations from chemistry transport models
- Stability in the climatological aerosol optical depth by components
- Optical properties of wildfire-induced aerosols

NASA Terra Satellite [March 2000 – present]

courtesy of Prof. Di Girolamo at Univ. of Illinois

Multi-angle Imaging SpectroRadiometer (MISR)



Nine view angles at Earth surface: 70.5° forward to 70.5° backward

Nine 14-bit pushbroom cameras

275 m - 1.1 km sampling

Four spectral bands at each angle: 446, 558, 672, 866 nm

400-km swath: 9-day coverage at equator, 2-day at poles

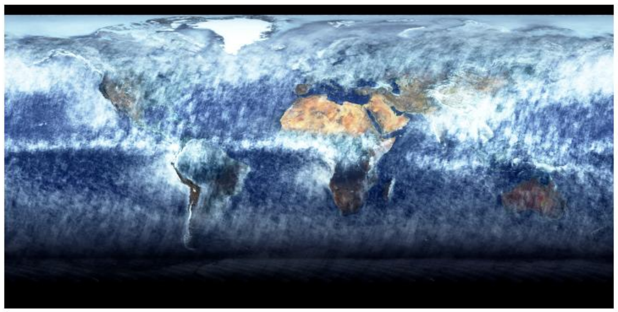
7 minutes to observe each scene at all nine angles

courtesy of Michael Garay at JPL

Example MISR Standard Products

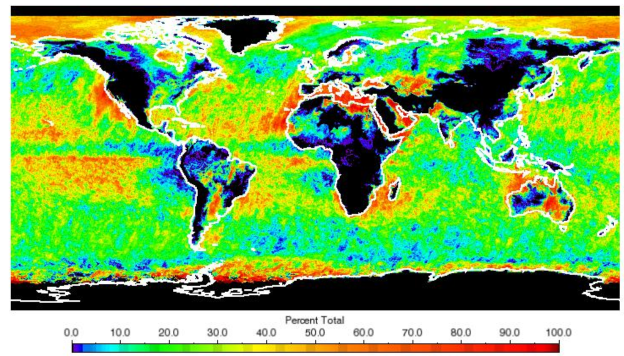
Radiance

Radiance AN Summer 2005 F04_0025 (All, Natural color, Hist. equal.)
Summarizes L1 GRP_TERRAIN/GRP_ELLIPSOID, Rad/RQI field F03_0024, 0.5 deg res



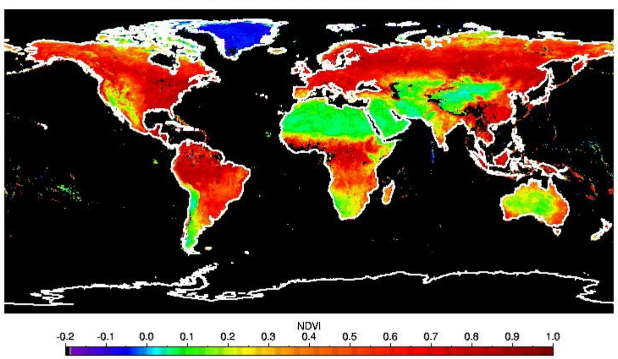
Cloud Top Height

Height Percentage, < 0.5, w/o wind correction, Summer 2005 F02_0024
Summarizes L2 TC_STEREO, StereoHeight field F08_0017

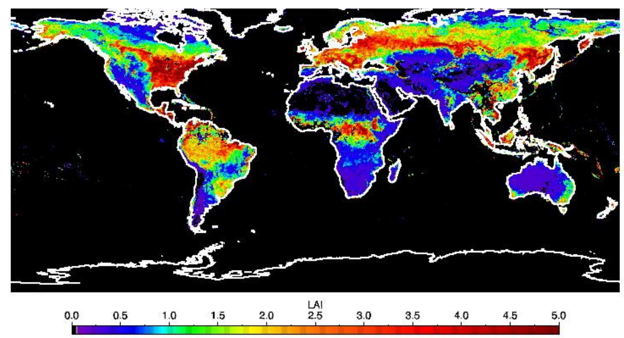


NDVI (normalized difference vegetation index)

NDVI Summer 2005 F04_0017
Summarizes L2 AS_LAND, NDVI field F06_0017, 0.5 deg res

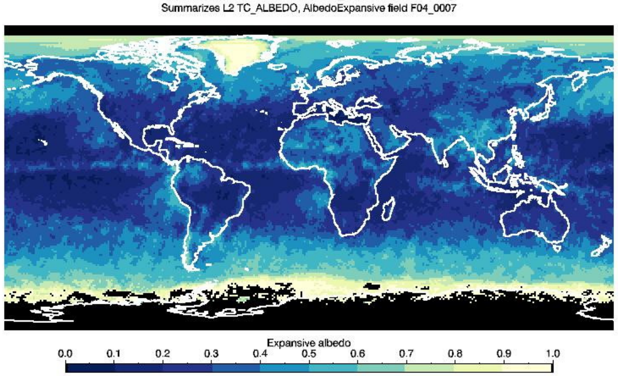


LAI (leaf area index)



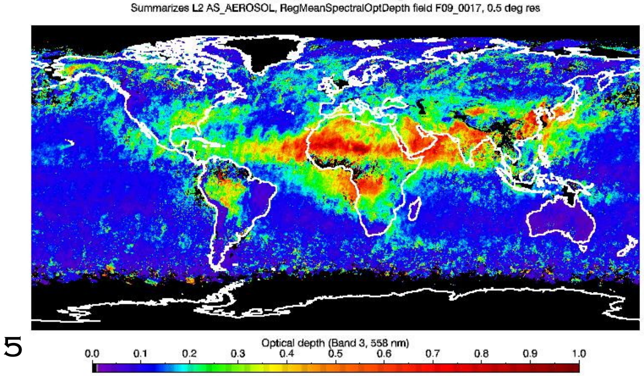
Albedo

Expansive albedo Summer 2005 F06_0012, Red band, 1 deg
Summarizes L2 TC_ALBEDO, AlbedoExpansive field F04_0007

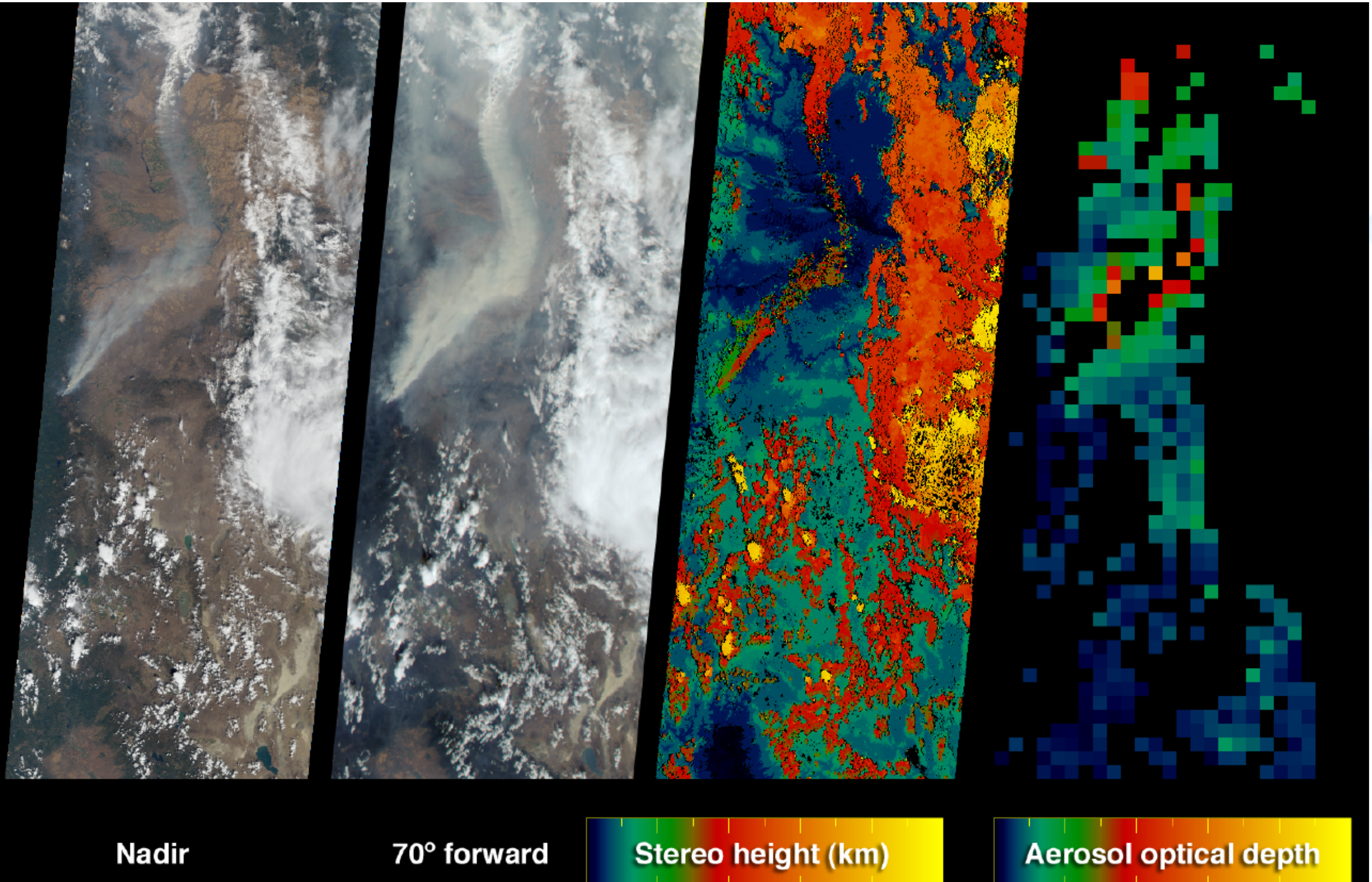


AOD (aerosol optical depth)

Optical depth Summer 2005 F06_0017
Summarizes L2 AS_AEROSOL, RegMeanSpectralOptDepth field F09_0017, 0.5 deg res



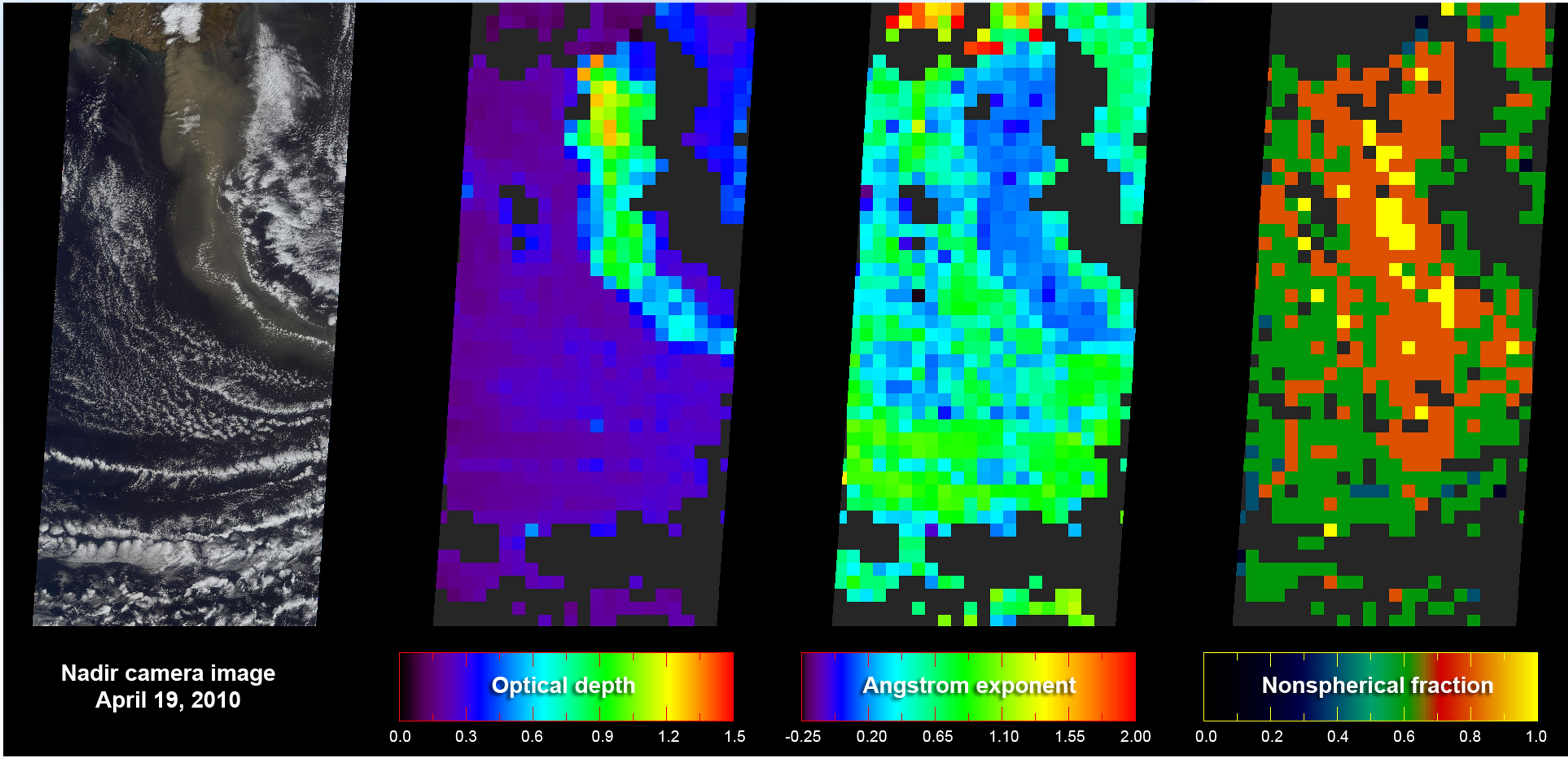
courtesy of Michael Garay at JPL



B&B Fire Complex - Oregon

courtesy of Michael Garay at JPL

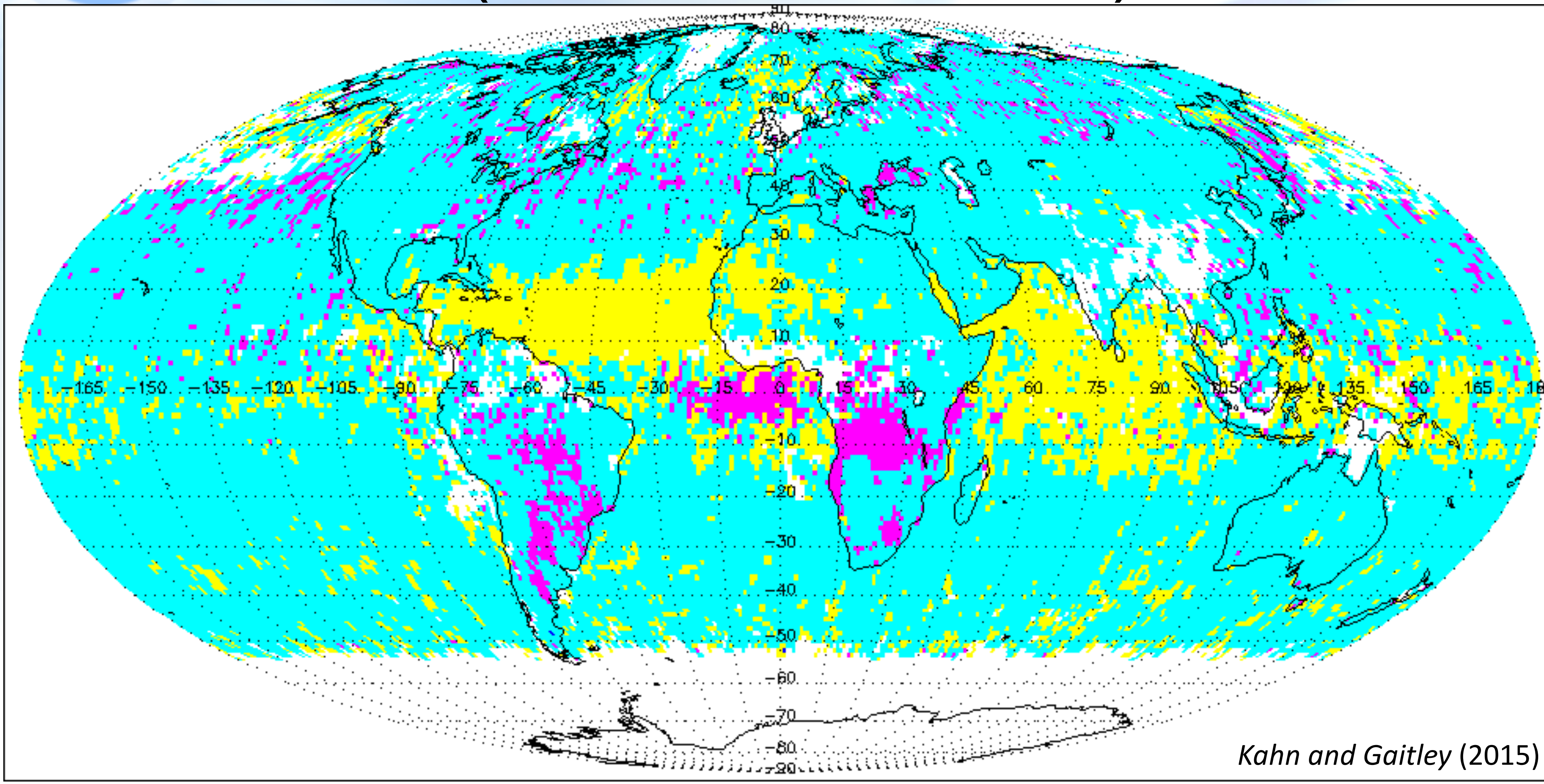
Aerosol particle properties from MISR



MISR views of Eyjafjallajökull – 4/19/2010

courtesy of Michael Garay at JPL

74 Aerosol Mixtures (Standard Product)

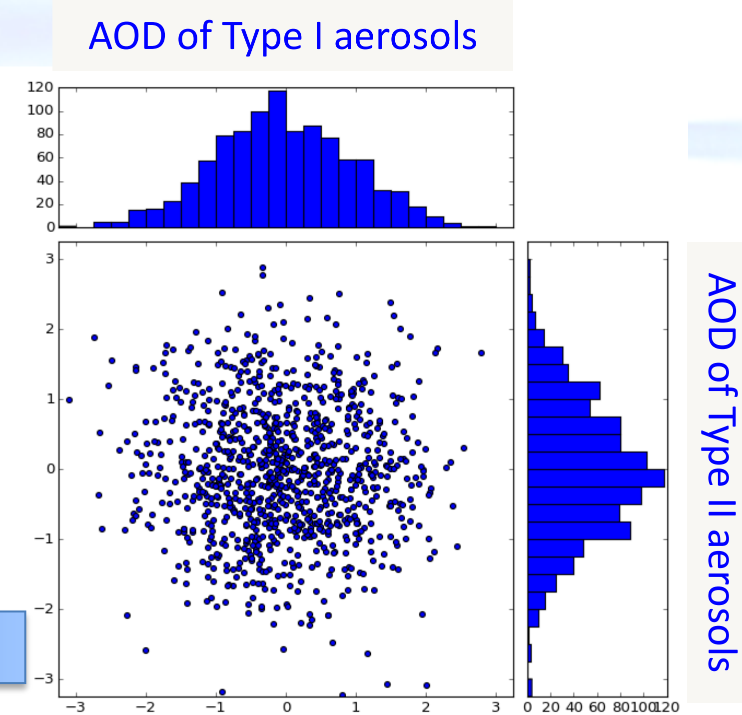


Kahn and Gaitley (2015)

Key
- Spherical Non-Absorbing
- Spherical Absorbing
- Non-Spherical
- Spherical Absorbing + Non-Spherical (Tie)
- Spherical Non-Absorbing + Non-Spherical (Tie)
- Spherical Absorbing + Spherical Non-Absorbing (Tie)

MISR L3 Joint Aerosol (JOINT_AS) : algorithms based on *Braverman and Di Girolamo*, (2002)

- Global statistical summaries of MISR Level 2 AOD: 8-dimensional histograms.
- Resolution: 5 x 5 degrees (60 S – 60 N) & monthly



mean, standard deviation*, skewness* and extreme values*

- The size of data files is significantly reduced from the Level 2 data, while approximating key information (marginal distributions and approximate moments of 8 aerosol types).

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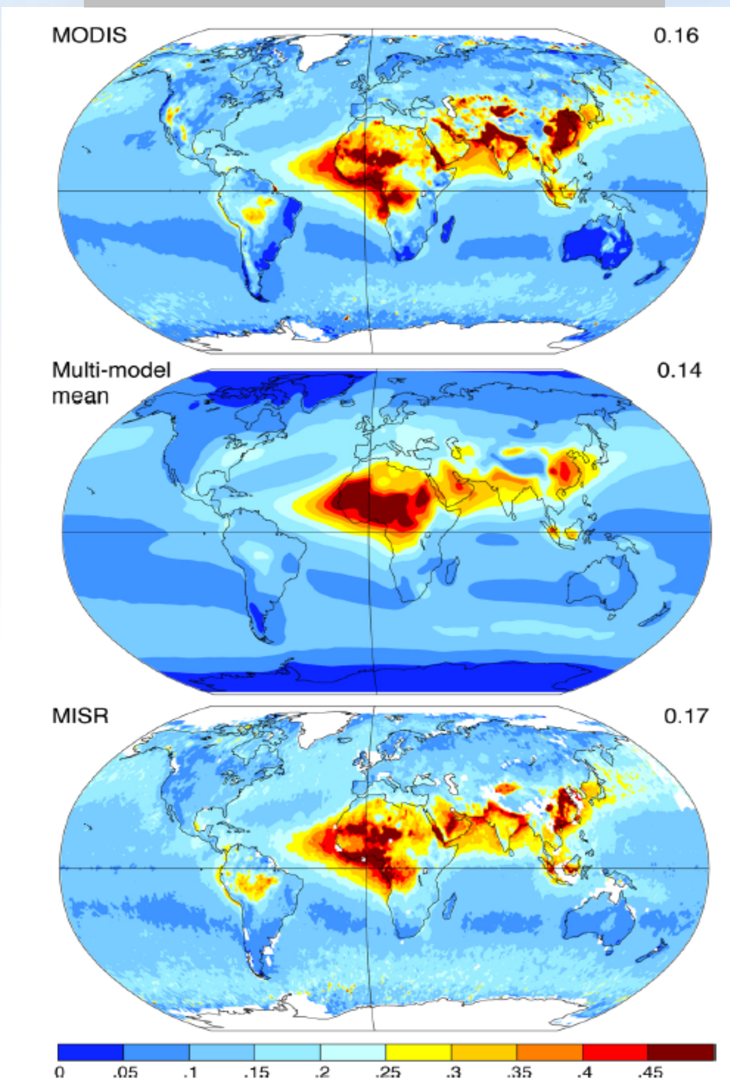
- Comparison of MISR Joint Aerosol Product with simulations from chemistry transport models
  - *Lee et al.* (2016), Climatology of the aerosol optical depth by components from the Multi-angle Imaging SpectroRadiometer (MISR) and chemistry transport models, ACP.
  - *Lee* (2016). AOD_monthly_2000-MAR_2016-FEB_from_MISR_L3_JOINT.nc, https://doi.org/10.6084/m9.figshare.3753321.v1
- Stability in the climatological aerosol optical depth by components
- Optical properties of wildfire-induced aerosols

Motivation

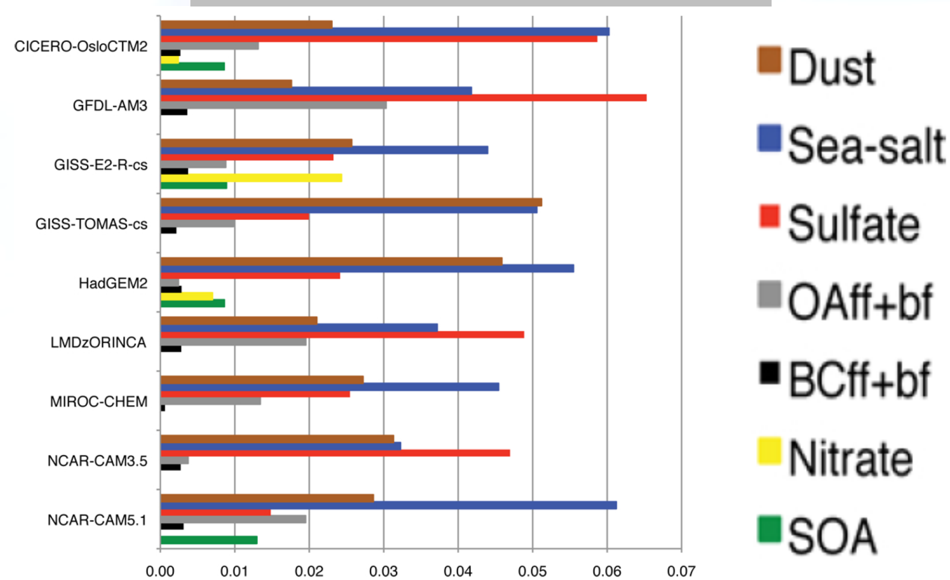
Shindell et al. (2013), Radiative forcing in the ACCMIP historical and future climate simulations

Total Aerosol Optical Depth (AOD)



- Total aerosol optical depth (AOD) from satellite observations (MISR, MODIS and so on) has been widely used to evaluate and constrain chemistry climate models (CCMs).
- However, chemistry model simulations show considerable spread in AOD by component.
- MISR provides **AOD for different aerosol types** that has potential to constrain and improve CCMs.

AOD by component



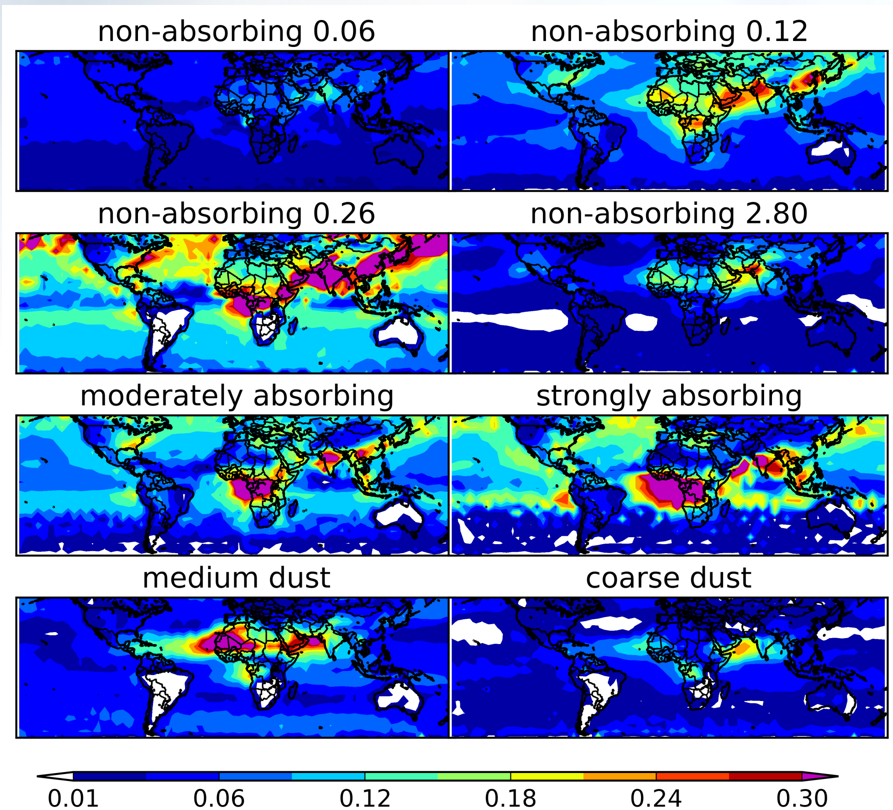
Objectives

- What is the added value of using AOD from MISR?
  - Investigate if multi-year MISR climatology of AOD by component could be used for evaluating CCMs.
  - Evaluate AOD for different aerosol types in CCMs by comparing multi-year MISR climatology.
- Why do we need information about AOD distributions other than averaged AOD?
  - Evaluate (and correct if possible) potential biases and outliers in MISR by examining characteristics of marginal distributions for each MISR aerosol type's AOD in various regions of interests.

MISR (July 2000-2013)

- 8 types:

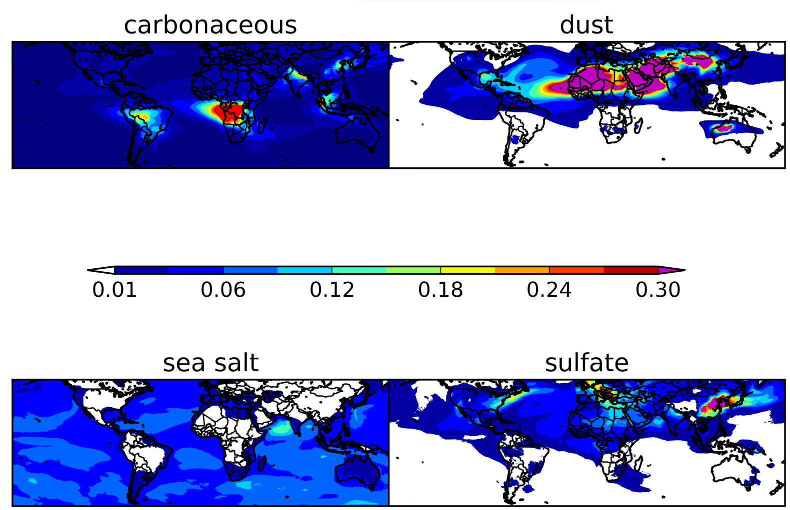
spherical nonabsorbing (4 sizes), spherical absorbing (small or large SSA), nonspherical (2 sizes)



NICAM (July 1-8, 2006)

- 4 types:

carbonaceous, dust, sea salt, sulfate



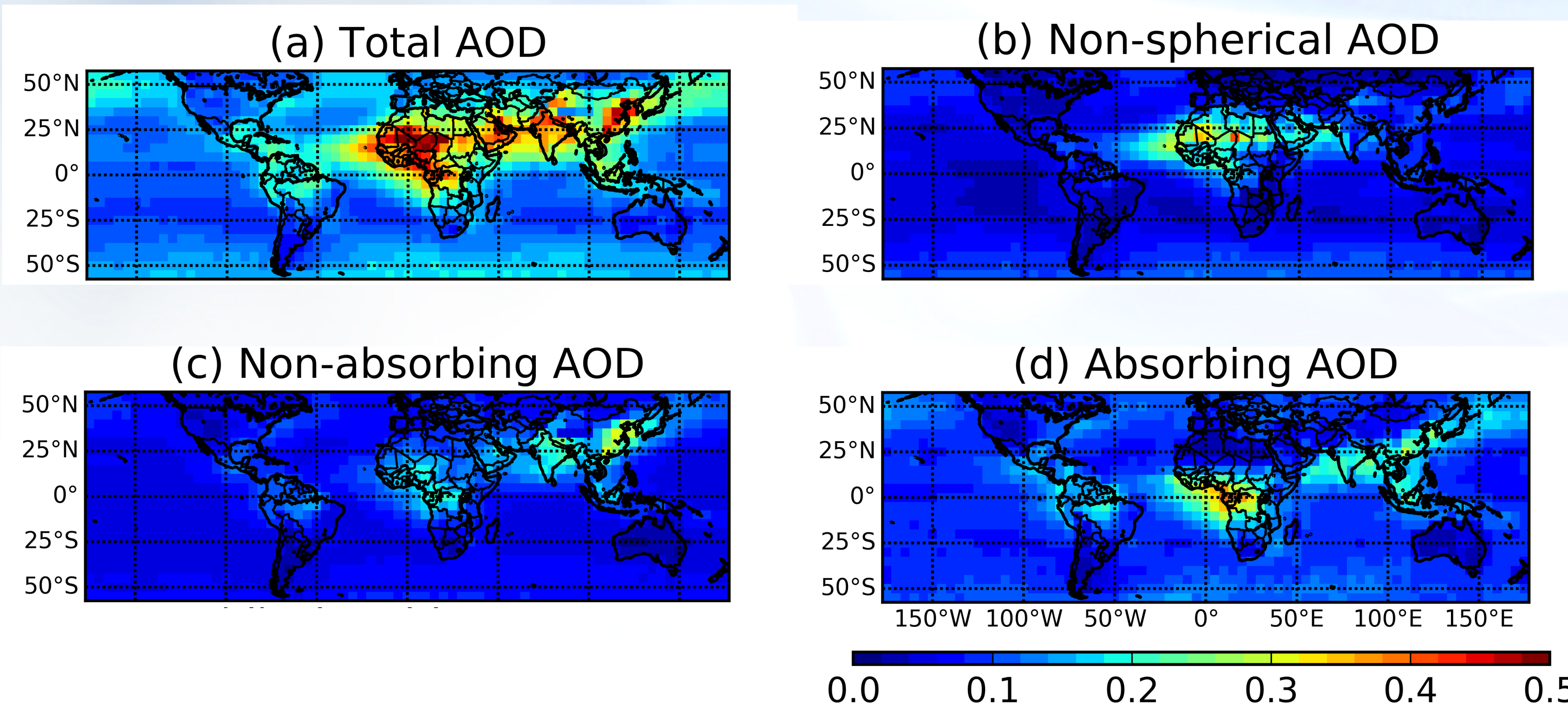
How to compare the 8 types in MISR and aerosol types in models?

AOD in MISR	AOD in models
absorbing aerosols (SSA 0.8 + SSA 0.9)	carbonaceous aerosols (od550bc+od550oa)
non-spherical aerosols	dust (od550dust)
non-absorbing aerosols	sulfate aerosols (od550so4)

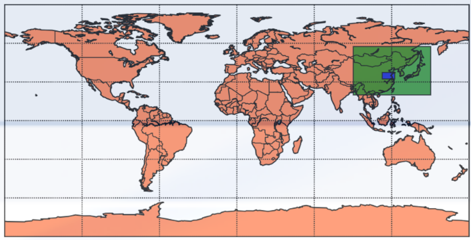
Single scattering albedo (SSA) = (scattering)/(scattering + absorption)

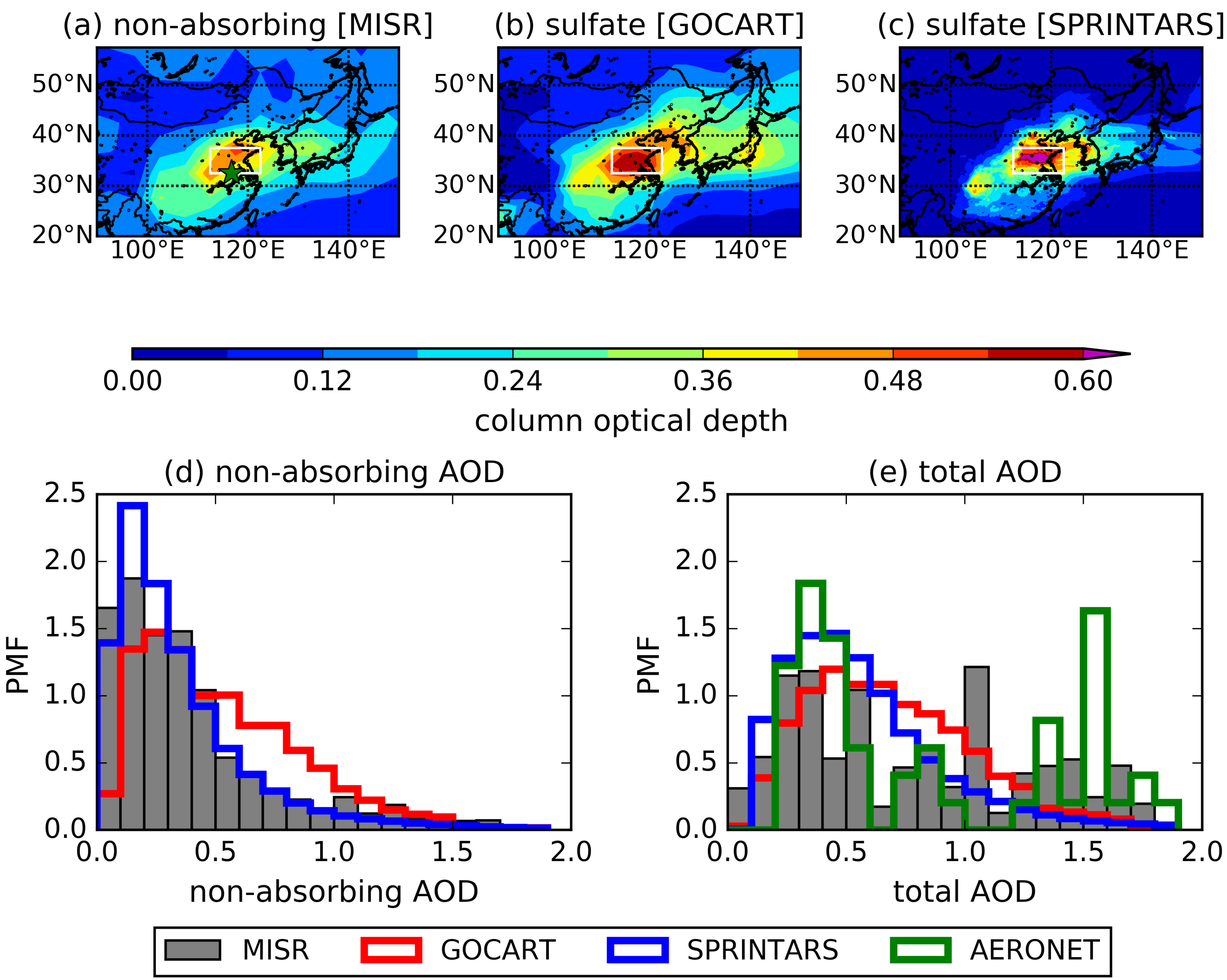
Mean optical depths from the MISR JOINT_AS product

- Averaged over the 17 years (March 2000 - February 2017)



East Asia [July]

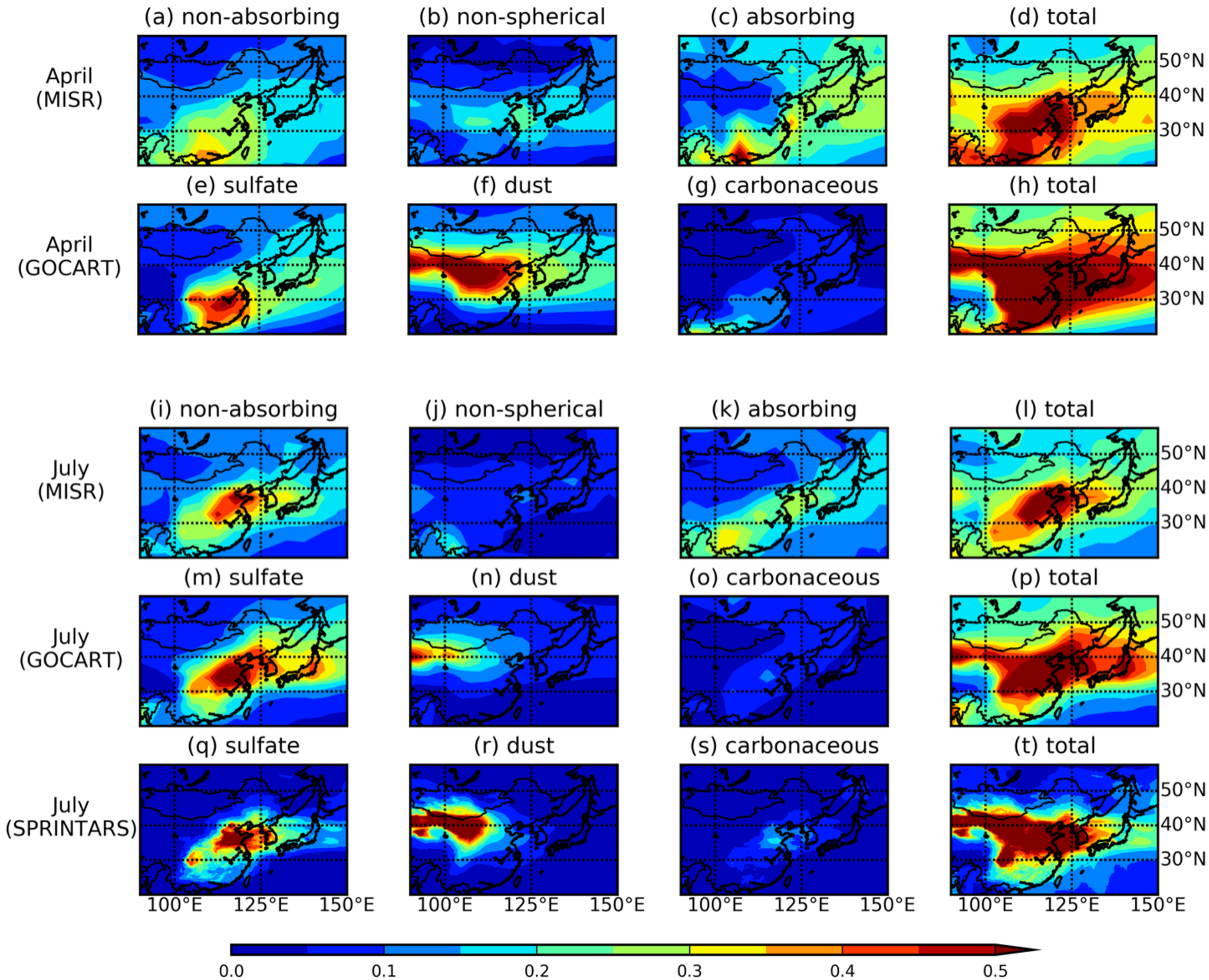




Aerosol Robotic Network (AERONET)

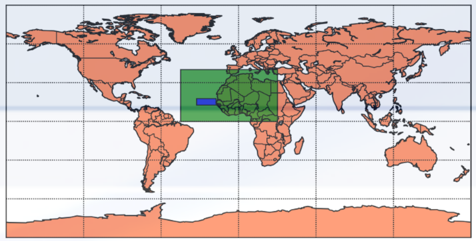
- Dominant type: nonabsorbing (sulfate)
- The observed distributions of total AOD do not follow the log normal distribution.

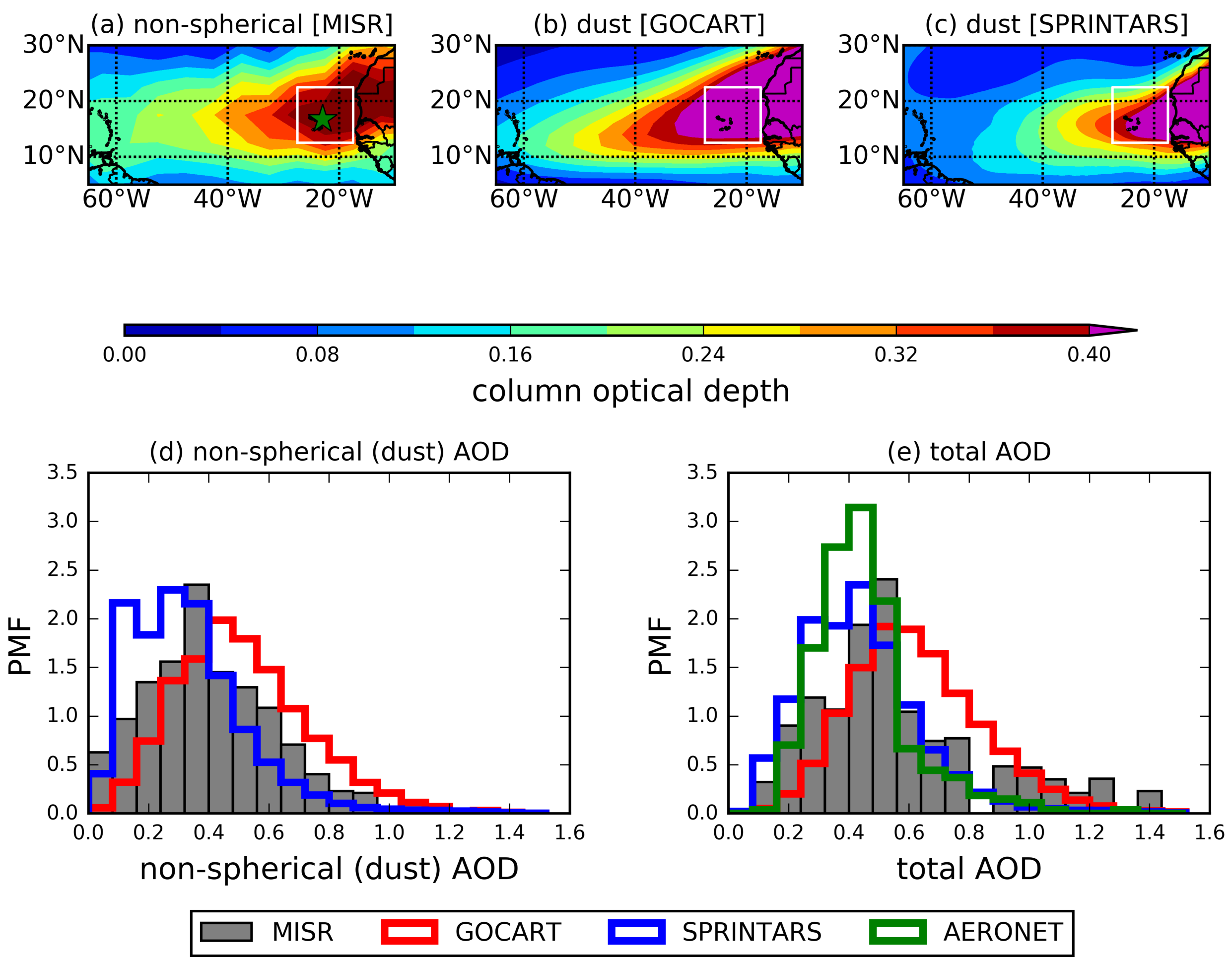
East Asia [April vs. July]



- The dominant sources of aerosols are different.
- MISR's non-spherical AOD in April

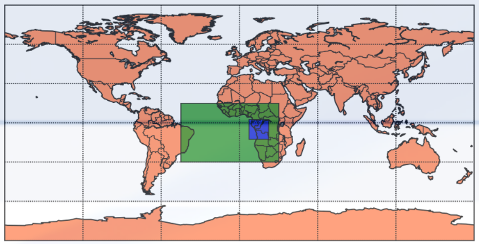
Eastern Atlantic [July]

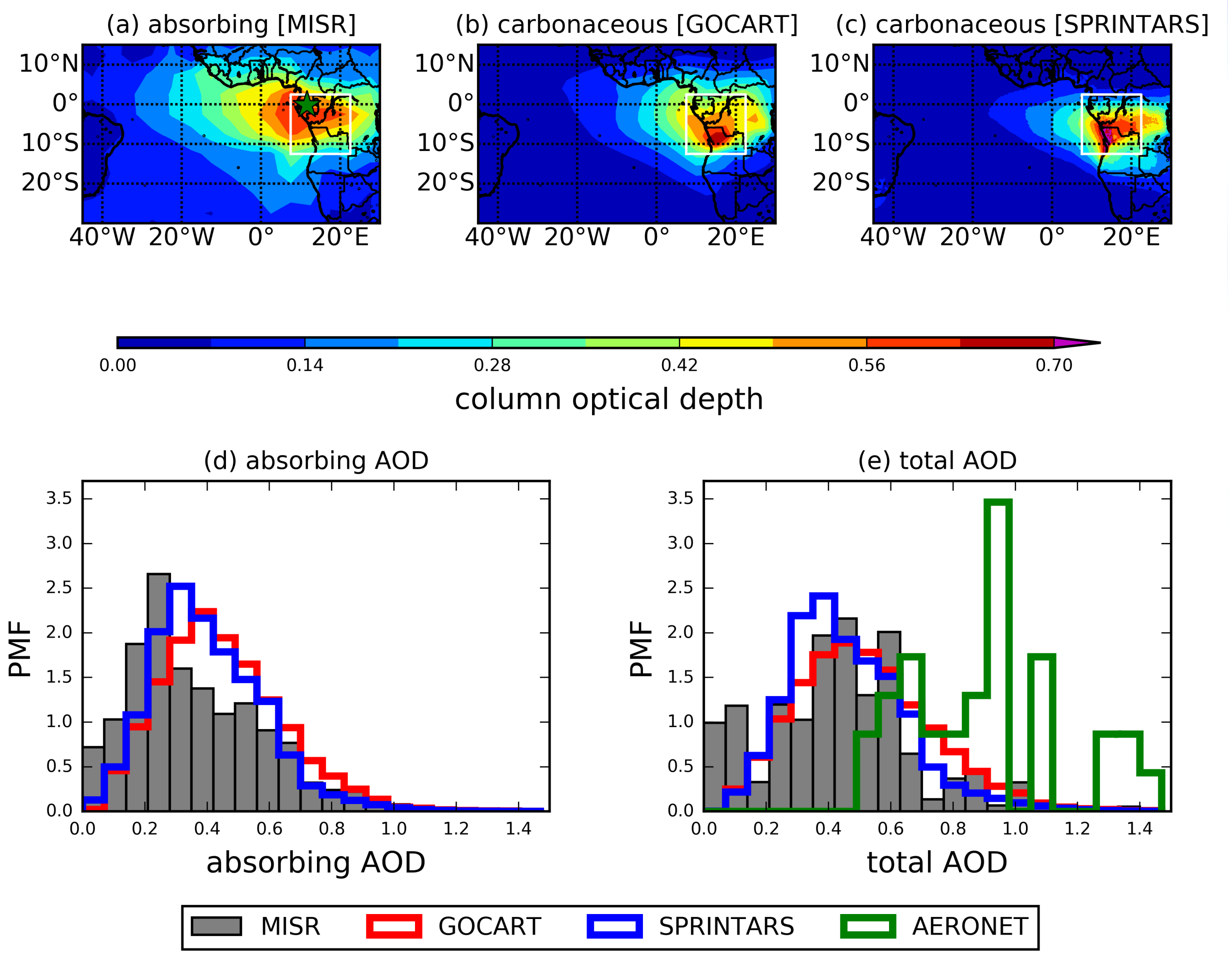




- Downwind from the largest source of dust aerosols on Earth
- Both nonspherical and total AOD in the region show good agreement with the simulated AOD.

Central Africa [July]





- Massive emissions of carbon aerosols are dominated by savanna and grassland fires.

- Despite the difference between MISR and the models, MISR's absorbing and total AODs over a longer period than the AERONET station provide a powerful model diagnostics.

Summary: part I

- MISR Level 3 Joint Aerosol product provides monthly climatological moments (mean, standard deviation, skewness and so on) of AOD for 8 different aerosol types.
- **The combined AOD of MISR aerosol types is comparable to simulated AOD** of non-absorbing (sulfate + nitrate), absorbing (BC + OA) AOD and dust AOD in chemistry transport models and chemistry climate models.
- In the three high-AOD regions studied, we show how the reliance on a single, dominant aerosol type can be inappropriate for certain locations and seasons.
- The new Joint Aerosol product based on MISR V23 will provide gridded monthly mean AOD and quality flags (public release is scheduled early 2019).

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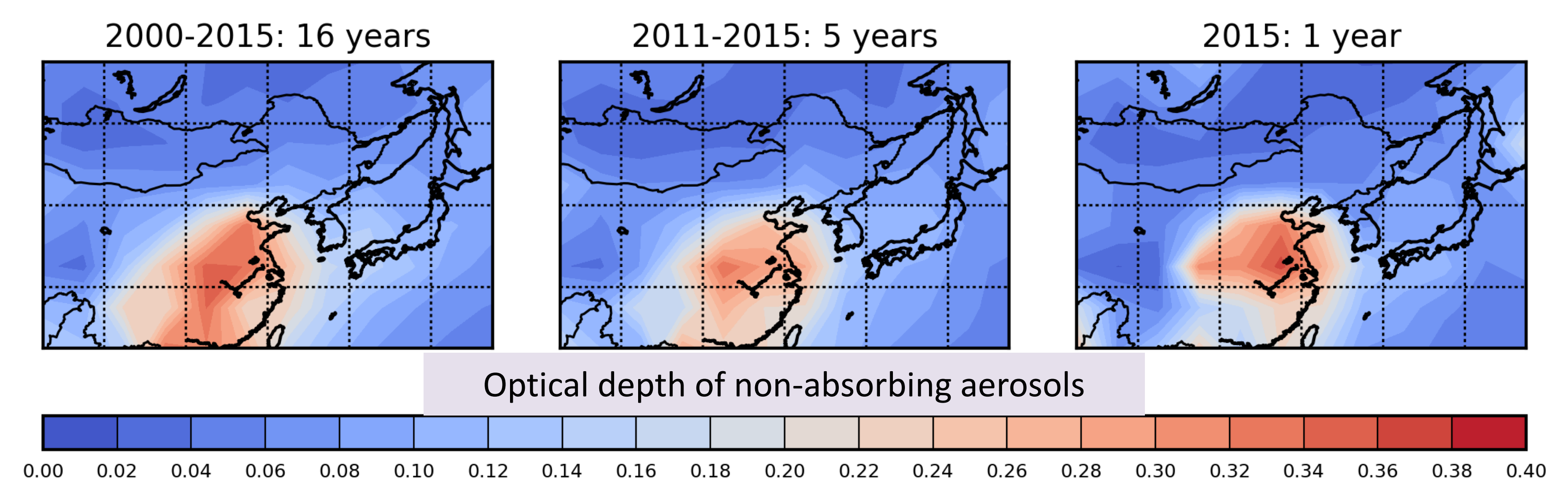
- Stability in the climatological aerosol optical depth by components
  - *Lee et al.* (2018), How Long should the MISR Record Be when Evaluating Aerosol Optical Depth Climatology in Climate Models?, Remote Sensing.
- Optical properties of wildfire-induced aerosols

Why do we care about the length of AOD observations?

- WMO standards require at least 30 years of observations without data gaps to define climatology for a variety of climate applications.
- NASA's Earth Observing System (EOS) satellites have provided unique AOD observations to study the Earth system over the last 16+ years.
- The chemistry models participating in the Aerosol Comparisons between Observations and Models (Aerocom) have substantially improved their capabilities in modeling aerosols. However, there remains uncertainty in both satellite observations used as reference datasets and AEROCOM model simulations even when we compare climatological AOD between the observations and models.

Objectives



- Are the 16 years of MISR measurements enough to build AOD climatology?
  - ✓ Quantify the impact of the length of observations on climatological mean AOD: measure stability of the AOD climatology.
- How do the Aerocom models simulate optical depths for different types of aerosols?
  - ✓ Evaluate the climatological seasonal cycle of AOD in the models.

Uncertainty of the multi-year mean AOD due to temporal subsampling

- Subsample the 17 seasonal means (September-October-November, SON) between 2000-2015 without replacement 100 times => 100 multi-year means of AOD

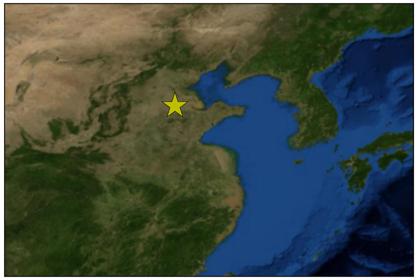
for sample_size (n) = 1, 15 # years

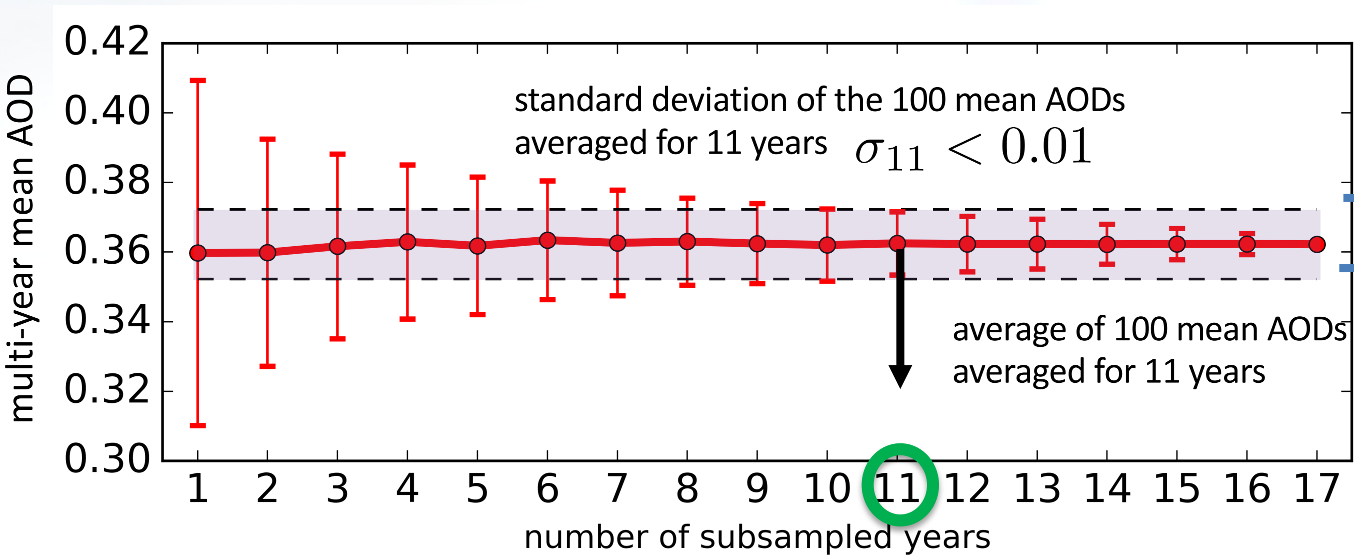
for number_sample = 1, 100 # random subsets

sub_climatology[ ] = CALC_MULTI_YEAR_CLIM( )

ex) for *n*=4, (2002, 2003, 2005, 2015) (2004, 2007, 2008, 2009).. (2002, 2003, 2004, 2015)

SON mean AOD over the 16 years: 0.362



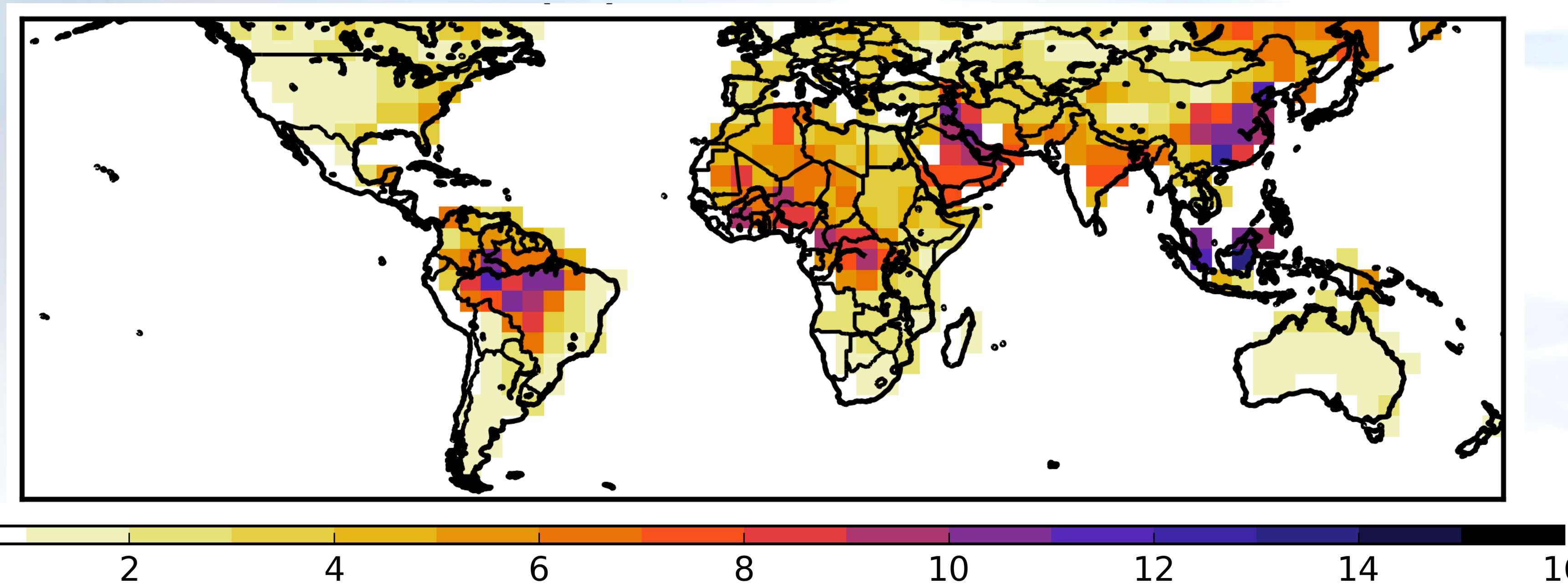


0.372 = 0.362+0.01

0.352 = 0.362-0.01

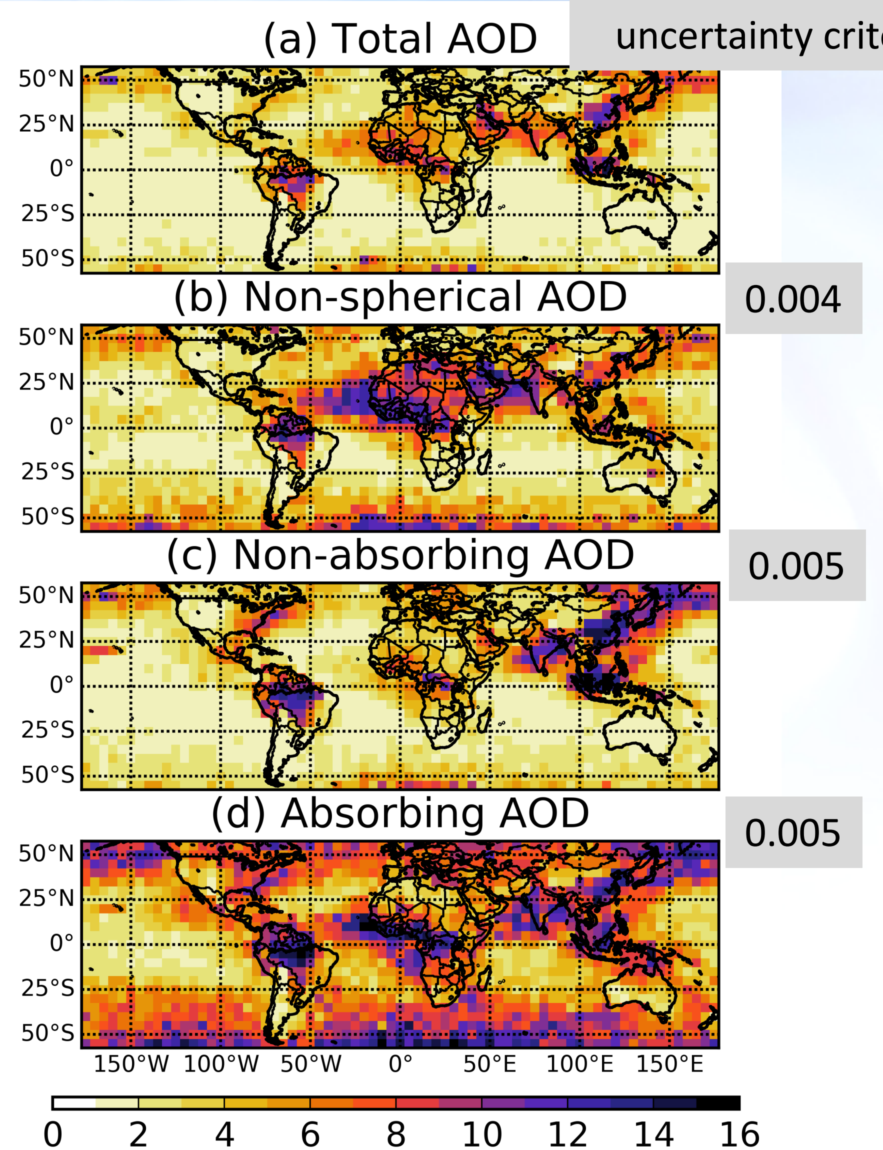
Clim. AOD-0.1 < $\bar{x}_n \pm \sigma_n$ < Clim. AOD +0.1

minimum # of years required to calculate climatological total AOD (annual mean) with the accuracy of 0.01



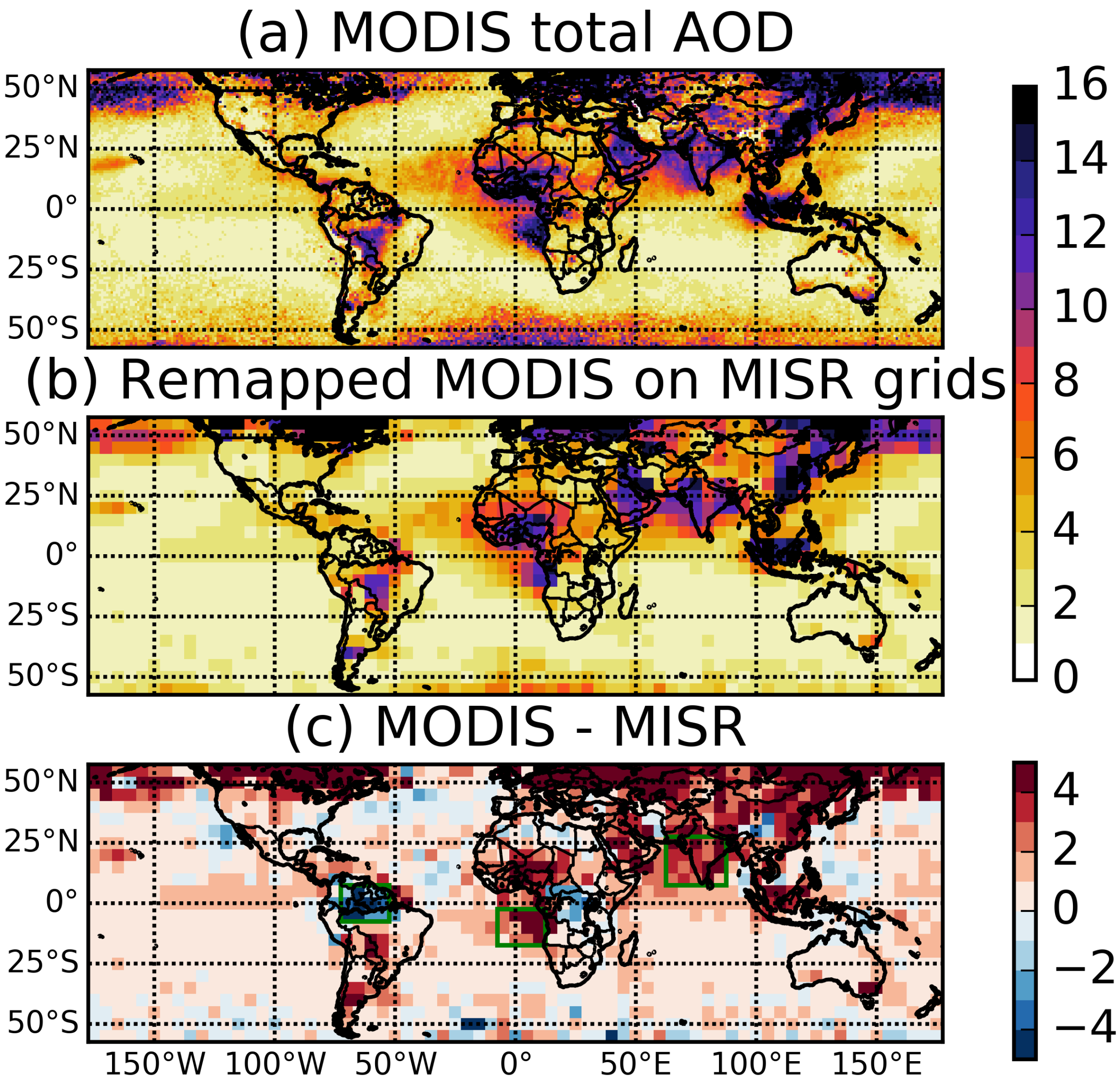
- Conversion of interannual variability in AOD into another quantity useful for studying climatology
- Overall, the 17-year observation record is valuable to define climatological AOD.
- In some regions (e.g. Amazon and Maritime continent), 17 years may not be long enough to build the climatology of annual mean AOD.
- Evaluation of simulated AOD needs to be done for the maximum overlap periods between observations and models.

Stability of the multi-year mean AOD by component



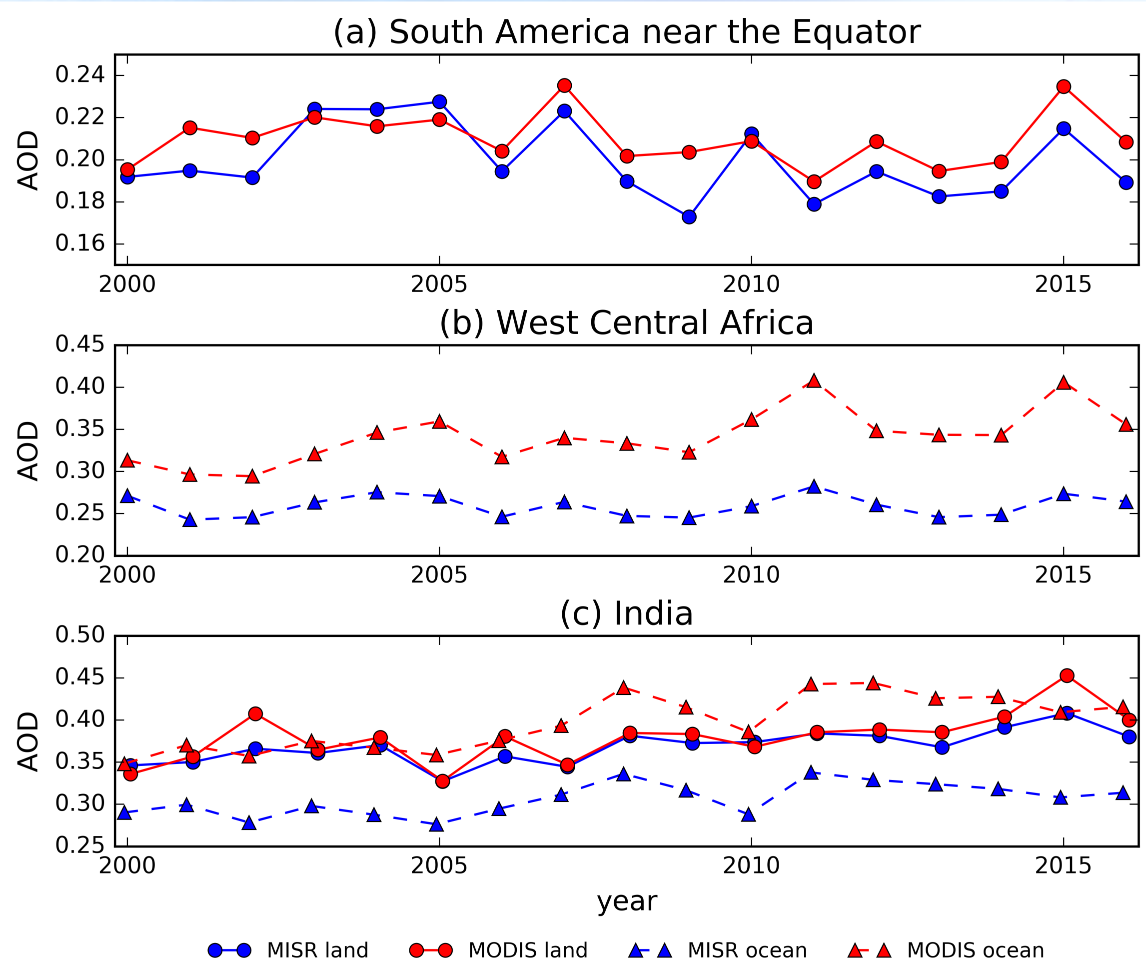
- The uncertainty of multi-year mean optical depth due to temporal subsampling becomes large when generating climatological AOD by components, especially for non-spherical and absorbing AOD.
- The uncertainty is considerable in major sources of aerosols (e.g. the Sahara Desert, Amazon, and Central Africa).

MODIS vs. MISR



- The minimum record length required to achieve stability in the total MODIS AOD climatology at high resolution (1° x 1°) even exceeds 16 years in many parts of the world.
- The record length is typically longer for MODIS than MISR with the exception of the Amazon and the Congo.

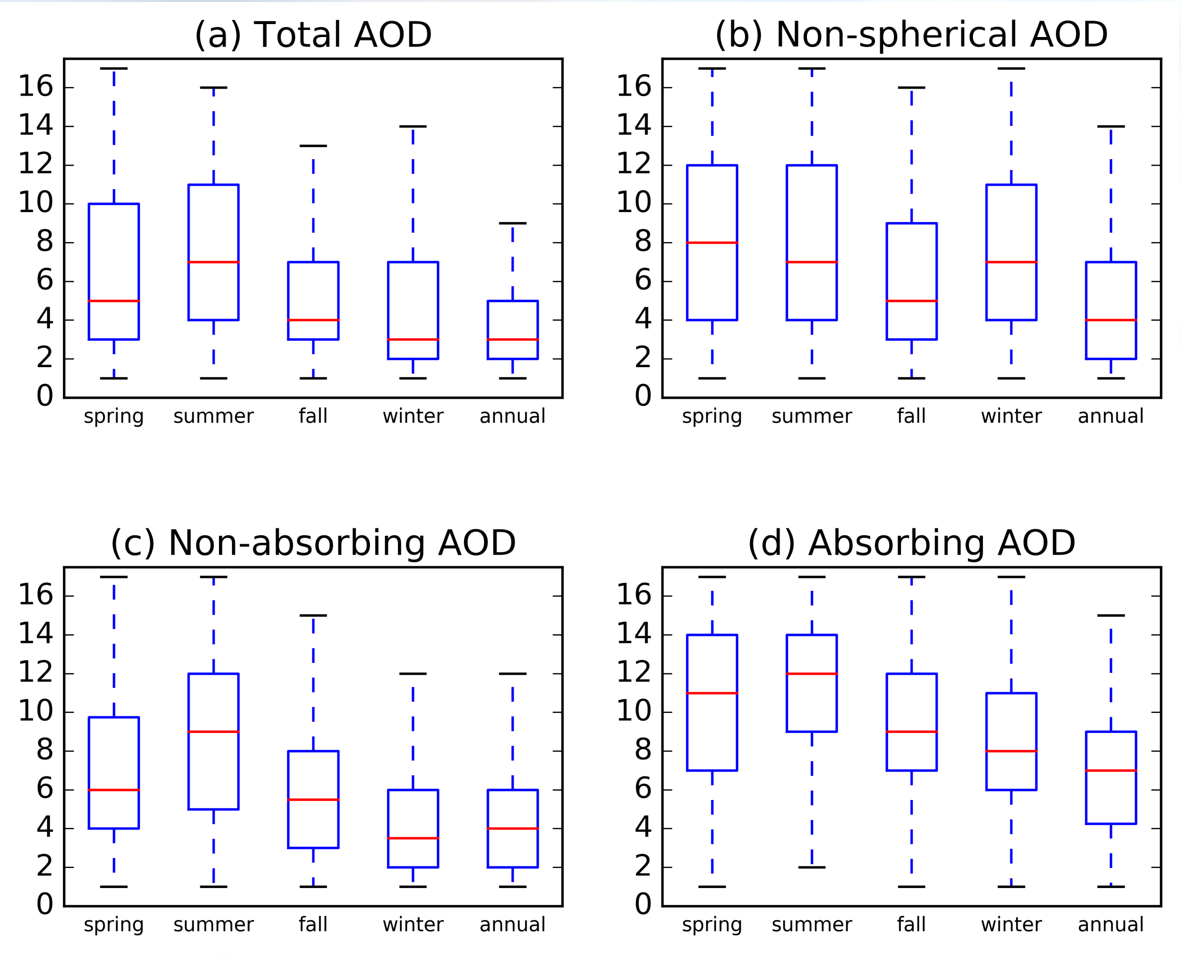
MODIS vs. MISR around India



- Both climatology and interannual variability in MODIS are higher than MISR. (e.g. Misra et al. [2016], Ramachandran and Kedia [2013], David et al. [2018]).
- AOD over ocean is greater than that over land in MODIS around India.
- In contrast, MISR's AOD is greater over land than ocean.

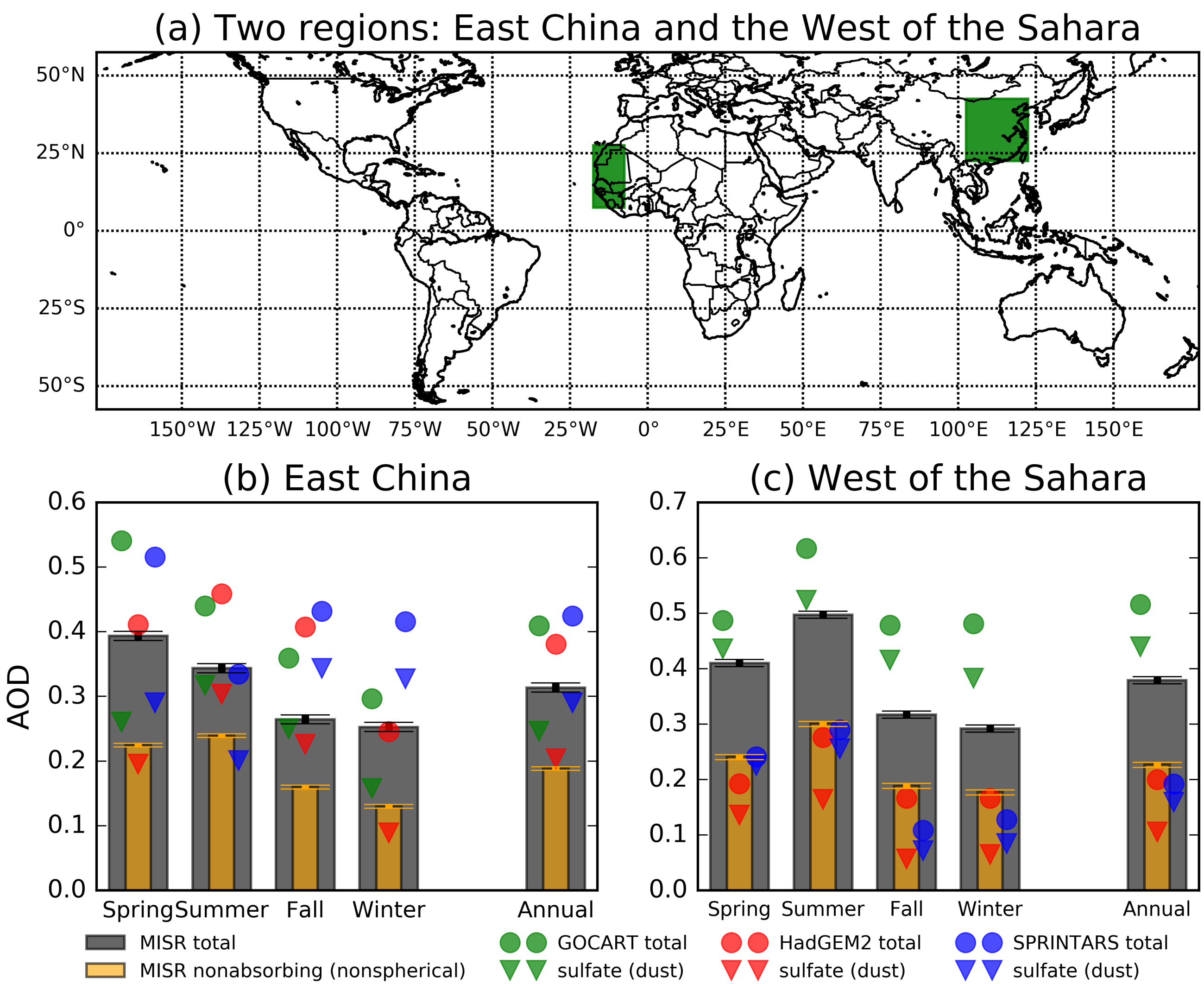
How long is long enough to define stable climatological AOD?

The global median of the minimum years required to obtain the sample standard deviation less than the predefined accuracy levels (0.01 for total AOD, 0.004 for nonspherical AOD, and 0.005 for nonabsorbing and absorbing AOD) for each season and annual mean



- The MISR AOD observation for the last 18 years and its temporal subset may provide enough information to examine global mean optical depths for different types of aerosols and possibly, their radiative forcing with quantitative uncertainties.
- However, the stability varies considerably by locations even for the annual mean AOD climatology.

The seasonal cycle of simulated AOD (March 2000 – February 2005)



- In East China, the observed total AOD peaks in spring whereas the nonabsorbing AOD is highest in summer. Only GOCART simulation reproduced these observed seasonal cycles.
- In the west of the Sahara Desert, both total and non-spherical AOD peak in summer. This seasona cycle is well represented in all three models.

Summary: part II

- The length of satellite observation records affect the climatological aerosol optical depth (AOD), especially the multi-year mean of optical depth by components.

- At a global scale, the climatological AOD defined using more than 10 years of MISR data is stable.

- However, the large uncertainty of climatological mean AOD in some regions indicates that we do need longer observations to obtain reliable AOD climatology by components.

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  - *Lee et al.* (2018), Characterization of wildfire-induced aerosol emissions from the Maritime Continent peatland and Central African dry savannah with MISR and CALIPSO aerosol products, JGR.

Motivation

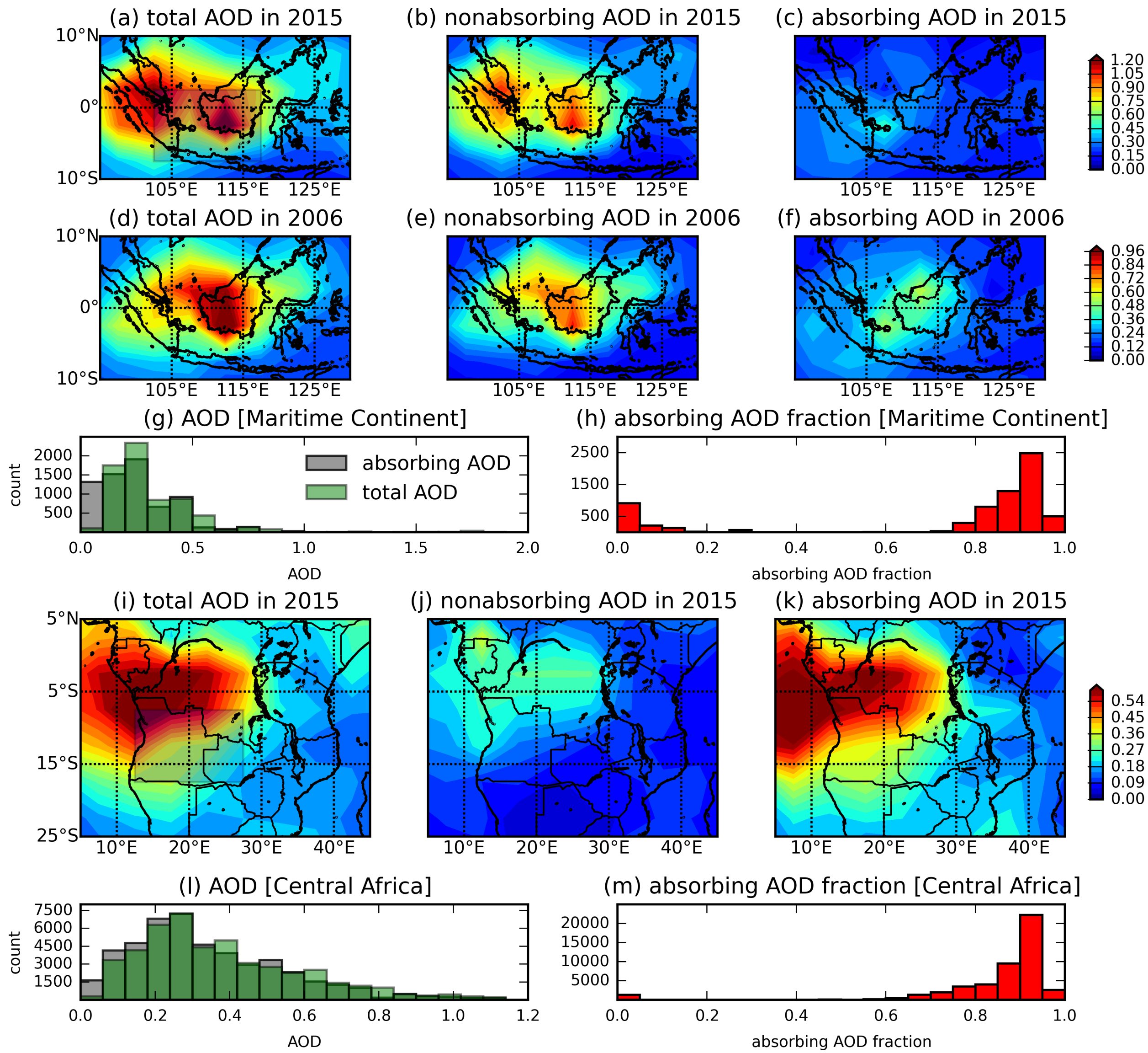
- The strong El Niño related wildfire over Indonesia between late June and October in 2015 emitted about 1.35 Gt of CO_2 equivalents (almost same as the total emission from Japan).
- The wildfire also became a massive source of aerosols. Multiple countries suffered from the fire related smog.
- The burned area's soil is abundant in **peat**. Peat is partially decayed vegetation or organic matter and highly combustible during dry season.
- Can we use satellite observations to characterize optical properties of the aerosols from 2015 Indonesia Fire?

types of vegetation and soil

smoke composition

Optical properties of aerosols

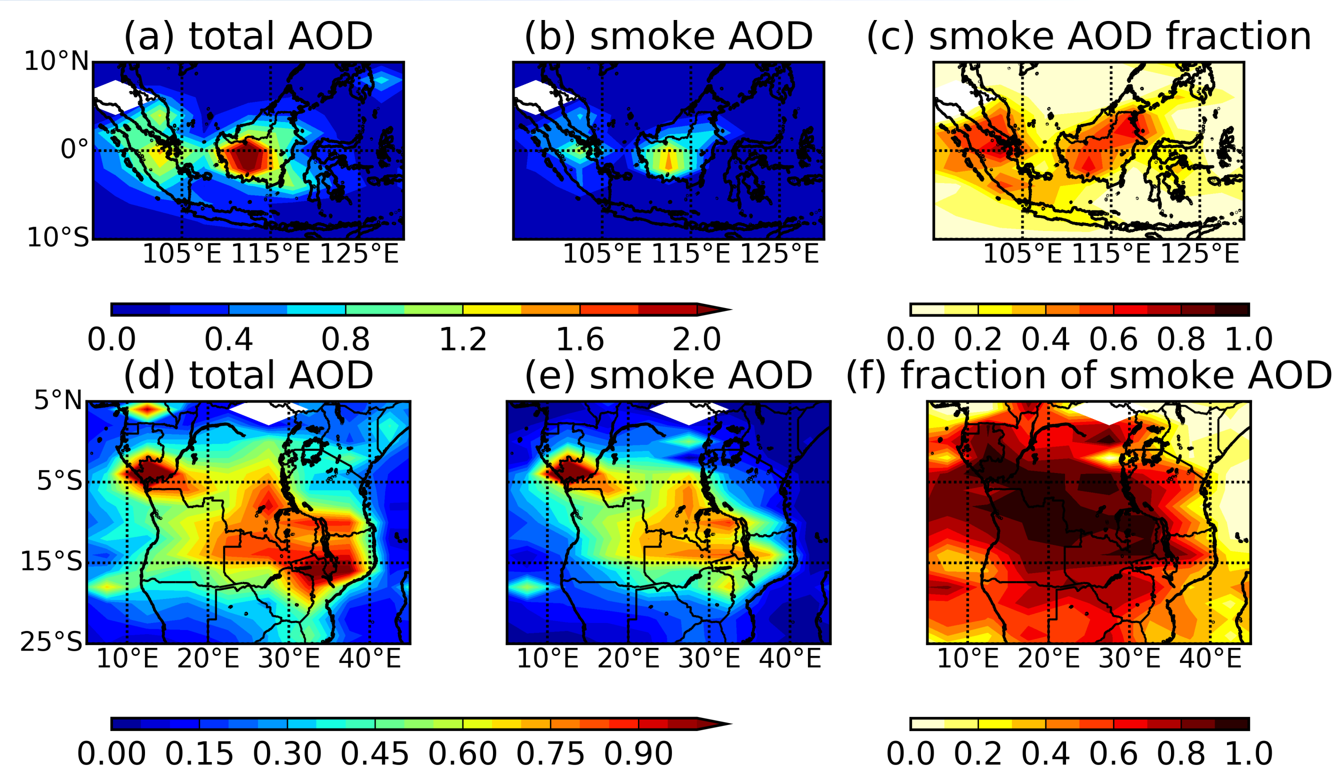
Comparison of aerosol types in MISR between the Maritime Continent and Central Africa



- The aerosol optical properties retrieved from satellite-based observations with consistent retrieval for years enable investigation of the aerosol characteristics reflecting terrestrial environments (burning conditions).

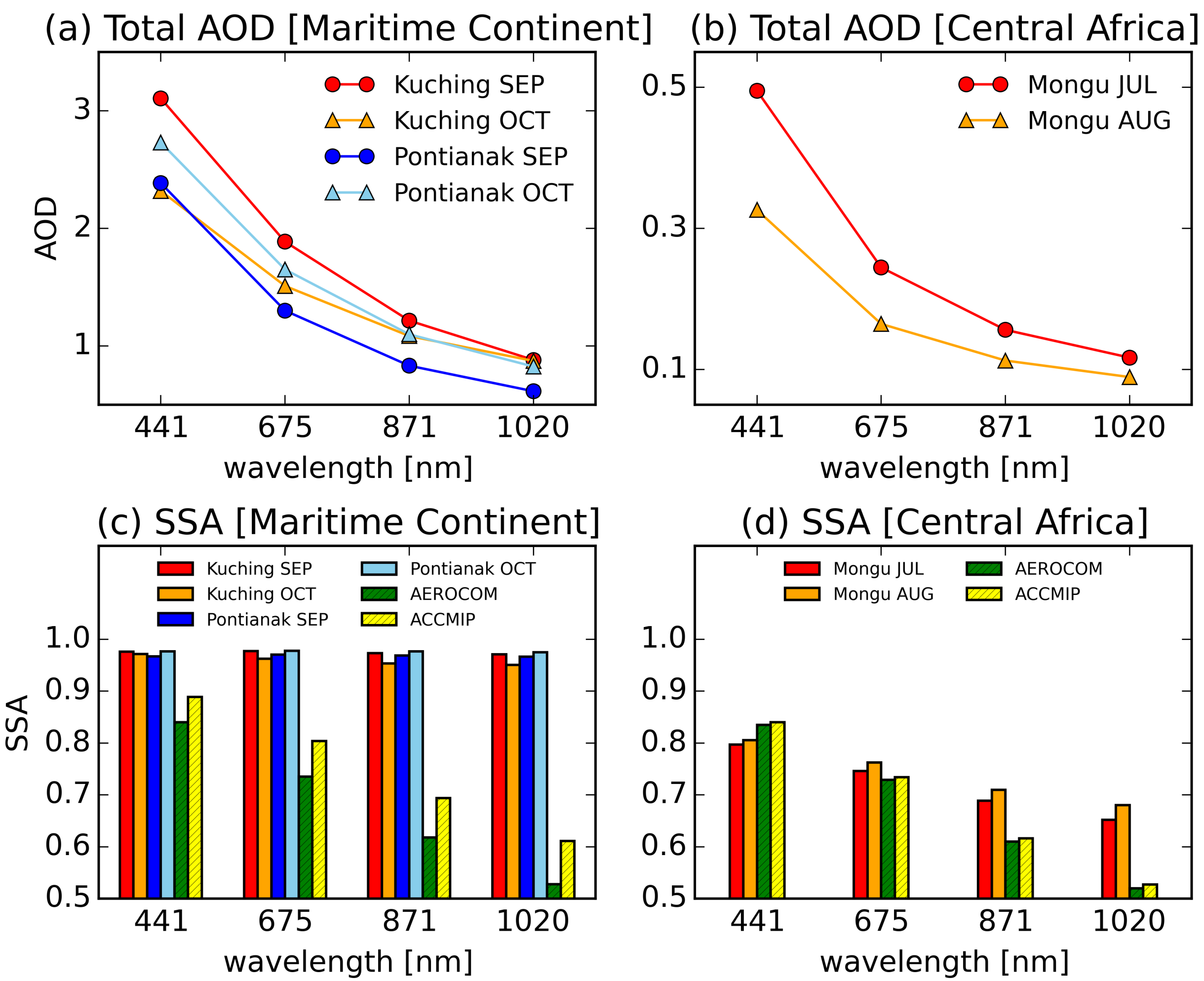
- The absorbing aerosols account for a significantly lower fraction in smoke plumes from the Maritime Continent than those from Central Africa.

Comparison of aerosol types in the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO)



- The lower fraction of smoke AOD over the Maritime Continent compared to Central Africa is consistent with the MISR observation.

AERONET measurements and optics simulations



- The smoke plumes from wildfires in the Maritime Continent reflect shortwave radiation more efficiently than those in Central Africa.

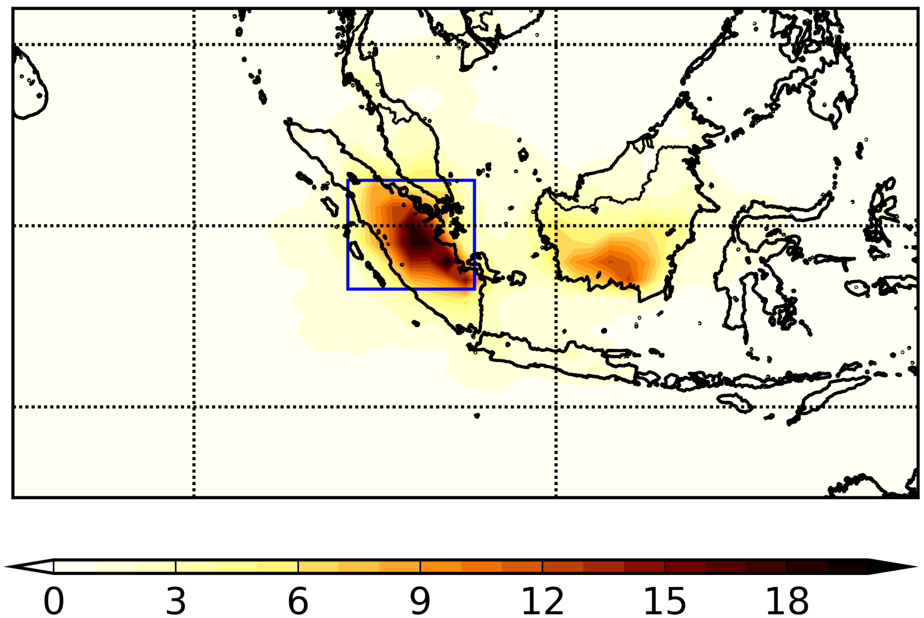
- Idealized simulations of SSA using the ratios of black carbon aerosol fluxes used for AEROCOM and ACCMIP: The calculated SSA for Central Africa is comparable to the observations, whereas the observed SSA is much larger than simulated SSA in the Maritime Continent.

Summary: part III

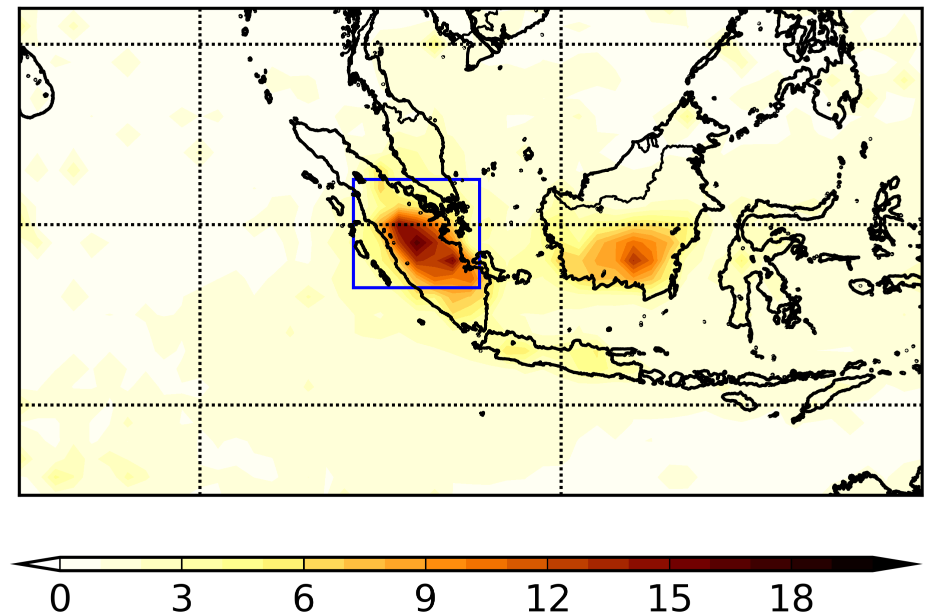
- The absorbing aerosols account for a significantly lower fraction in smoke plumes from the Maritime Continent than those from Central Africa.
- The wildfire-aerosol-climate feedback processes largely depend on the terrestrial environment sand fire-burning conditions (Maritime Continent peatland vs. Central African dry savannah).
- The optical properties of carbonaceous aerosol mixtures used by AEROCOM models may overestimate emissions for absorbing aerosols from wildfires over the Maritime Continent.
- Our working hypothesis is that organic aerosols and gaseous ammonia in smoke plumes from smoldering fire and formation of secondary ammonium aerosols may play an important role in optical properties of the aerosols in smoke plumes.

Column NH_3 (2015 September 01 - October 31)

Infrared Atmospheric Sounding Interferometer (IASI)

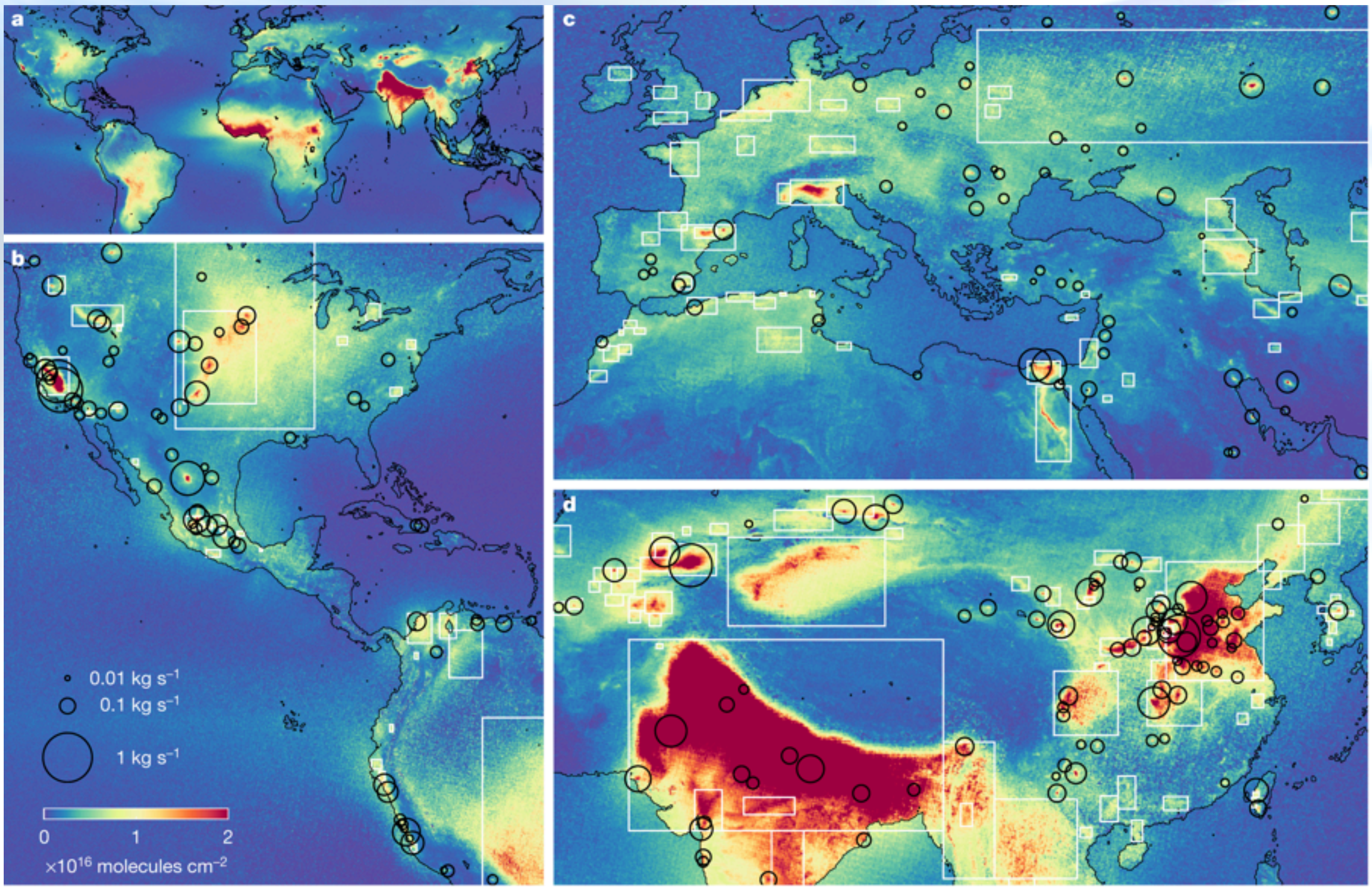


Cross-track Infrared Sounder (CrIS)



Our case study indicates that massive ammonia emissions from smoldering fire can influence optical properties of smoke plumes: the more NH_3 emissions, the more scattering.

IASI nine-year oversampled average, hotspots and source regions



from *Van Damme et al.* [2018], Industrial and agricultural ammonia point sources exposed, Nature.